Assessing Mid-Holocene Aridity in Central Ohio Using a Multi-proxy Lake Based Approach

Research Thesis

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by

Paul Soltesz

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Project Advisors:
Professor David Porinchu, Department of Geography, University of Georgia and
Professor Bryan Mark, Department of Geography, The Ohio State University

Abstract

The continental interior of North America experienced a period of prolonged warming and aridity during the Mid-Holocene. Although the general span of maximum warmth and dryness is believed to have been about 6,000 years BP during the Holocene Thermal Maximum, the regional variability, environmental response, and timing of this event are complex and not fully understood. To better understand the nature of this period for Central Ohio three paleolimnologic proxies (Carbon to Nitrogen ratios (C:N), percent organic Carbon as estimated through loss on ignition (LOI), and sub-fossil midge remains) are analyzed from a sediment core collected from Smoot Lake (Licking County, Ohio) to reconstruct the Holocene paleoenvironmental record for Central Ohio. Sub-fossil midge remains in particular are a useful paleolimnologic proxy that has not yet been utilized in the Midwest. The proxies are interpreted as indicators of effective moisture from interpreted changes in lake levels. This study found that an extended period of low lake levels existed during the early Holocene reaching maximum dryness at 8,500 years BP with levels recovering by 7,000 years BP. Another shorter period of aridity is centered around 3,500 years BP. This study demonstrates that sub-fossil midge remains are a valuable proxy for changes in lake levels. Should future climate return to the warmer levels recorded during the Mid-Holocene, effective moisture is also likely to decrease which will have ecological and societal implications for Central Ohio.

Introduction

Modern global climate models (GCMs) suggest that the global mean temperature will increase between 1.8°C and 4.0°C by the year 2099 (IPCC, 2007). In the Midwest, and specifically Ohio, temperature increases of this magnitude may have severe impacts environmentally and economically. Higher temperatures will increase drought stress and vulnerability to forest fires (Wuebbles and Hayhoe, 2004) as well as initiate a myriad of problems for agricultural production (Evrendilek and Wali, 2004). Improved understanding of how terrestrial and aquatic ecosystems in Ohio will be impacted by projected warming requires a better understanding of climate variability at a regional level. One approach to improve our understanding involves studying past climate change and assessing regional responses to these changes in climate.

Palaeolimnological Studies

Palaeolimnology incorporates the analyses of lake sediments and presents an excellent means to study paleoclimate and past environmental change. Lake sediments act like archives, faithfully recording and preserving a record of ecosystem conditions. Biological, physical, and geochemical proxies can be extracted from lake sediment cores, and can be used to provide detailed reconstructions of late Quaternary environmental conditions. Dating of cores through radiometric measures such as accelerated mass spectrometry (AMS) ^{14}C or ^{210}Pb dating, and the development of associated age-depth models, provides chronologic control for the recovered sediment cores. It is desirable to use multiple proxies when interpreting sediment records as this permits a more comprehensive characterization of the nature of past environmental change and enables researchers to address the relative role of various forcing factors in influencing the system (Birks and Birks, 2006).

However, multi-proxy studies are more complex given that they often involve incorporating multiple lines of evidence to develop an understanding of past changes. Data interpretation is further complicated given the complex nature of each individual proxy. For example, physical proxies such as percent loss on ignition (LOI) reveals the relative proportion of organic sediment and mineral materials, but it is not clear whether changes in LOI reflect absolute change in the amount of organic material or minerogenic material or some combination. Biotic proxies such as diatoms, chironomids, and cladocera, are often used for reconstructions of the environment and aquatic community composition and structure. Interpretation of biological proxies relies on the following assumptions: (1) the behavior of the organism in question in the past is similar to the modern; and (2) the distribution of the biotic proxy in question can be related to a single variable that can be modeled using a calibration set approach and transfer functions (Birks and Birks, 2006). It is important to note that proxies may reflect varying influences operating on different temporal or spatial scales. Nevertheless, multi-proxy paleolimnologic studies provide a means to observe and reconstruct past environmental change and identify the dynamics and causal mechanisms of complex systems (Birks and Birks 2006).

In this Study, a Holocene sediment record was recovered from Smoot Lake in Licking County, Ohio and analyzed for geochemical and biological proxies to develop a reconstruction of Holocene hydroclimate for central Ohio. Through analysis of insect remains (chironomids), carbon to nitrogen (C:N) ratios, and percent organic carbon content as estimated through loss on ignition (LOI), this project aims to recreate Holocene climate change and variability and environmental responses in Central Ohio. Although a part of a larger study whose aim is to recreate high resolution paleo-hydroclimatology records for the Midwest, this project's specific aim is to focus on the Mid-Holocene (about 6,000 years BP) to investigate and describe the magnitude of, and impacts associated with, a multi-century interval of aridity that characterized much of the continental interior of the United States during the mid-Holocene (Diffenbaugh et al., 2006). In particular, forcing factors and casual mechanisms for this drought are investigated. The Mid-Holocene is the last time that temperatures were warmer than present day (Shane and

Anderson, 1993; Shane, 1987) and thus present a likely analogue for conditions in the projected warmer near future.

Study Area

Smoot Lake is located at 40° 12`N, 82° 27’W in Washington Township, Ohio, a few miles south of the village of Utica in Licking County (Fig. 1). The study area is located in a primarily rural, agricultural region within the glaciated Allegheny Plateau. Although European settlement began in 1808, human habitation extends into pre-history with American Indian groups including the Mound Builders, the Adena, and the Hopewell present in the area (WTCP, 2003). The climate of the area is typical for central Ohio with a mean annual temperature of 51.5° F and an average precipitation of 41.48in based on a thirty year period from 1961-1990 (WTCP, 2003). The presence of the Allegheny Plateau results in orographic cooling as air masses move in an easterly direction, resulting in more moderate July temperatures, less extreme January temperatures, and increased precipitation for this region relative to the till plains located to the west (Shane and Anderson, 1993).

Smoot Lake is a closed double basin kettle lake located within a glacial outwash terrace (Forsyth, 1966). The lake was formed during the last glacial retreat, which occurred approximately between 12,800 and 14,300 years BP, with melting of the Wisconsin Ice Sheet (Ogden, 1966). As the ice sheet retreated, large sections of ice broke off and were embedded in the underlying glacial till. The ice blocks eventually melted and the depressions filled with water leading to the creation of kettle lakes. Today, Smoot Lake lies on private property and is ringed by a mixed second growth hardwood forest which in turn is surrounded by agricultural farmland. The surface area of Smoot Lake is approximately 128 meters by 183 meters (large basin) and covers 16.2 hectares when full (WTCP, 2003), but there is evidence that the lake was once larger covering a surface area of between 20.2-24.3 hectares (Hill, 1881). The lake has served as a water source for local agriculture and there is evidence of partial draining of the pond in the early 20th century (Coad, M., personal communication, 2010). A notable feature at Smoot Lake is the presence of a dredged inlet on the northern shore of the lake (Fig. 2), indicating further human influence. The presence of a nearly one meter thick, inorganic clay cap as the uppermost layer in the sediment core recovered from Smoot Lake is a clear indication of the regional timing of agriculture-related forest clearance.

Ohio's Late Quaternary Glacial and Climate History

Glacial expansion during the most recent glaciation, the Wisconsin, reached its maximum regional extent about 23,200 years BP (Glover et al., 2011). Ice advanced further south in the western half of Ohio creating the extensive till plain that characterizes much of this region. Although the timing was spatially heterogenous, in general the Laurentide ice sheet began to retreat northward at 21,000 BP. The recession of the Laurentide ice sheet was driven largely by variations in summer insolation with total Northern Hemisphere insolation beginning to increase at ~ 23,000 BP (Clark et al., 2009). Ice retreat was gradual across the state. Between 16,000 and 13,000 years BP tundra existed on the Allegheny Plateau. The tundra vegetation on the Allegheny Plateau was replaced by tree species such as spruce and pine, which today are associated with boreal forest communities. A sparsely populated tundra vegetation community characterized the till plains for approximately 1000 years immediately following deglaciation and slowly gave way to a dense forest tundra (Shane, 1987).

Between 13,500 and 11,000 years BP annual temperatures gradually rose, with increases of 2°C and 4°C estimated to have occurred for the Plateau and the till plains, respectively (Shane, 1987). By 12,000 years BP it is likely that all glacial ice had disappeared from Ohio (Glover et al., 2011). However, a notable departure from sustained post-glacial warming occurred between approximately 12,900 and 11,600 years BP. This event, known as the Younger Dryas (YD), resulted in an abrupt cooling that affected the entire Northern Hemisphere including the Midwestern United States. The expression of the YD was more pronounced on the Western Till Plains (3°-6°C cooler) and only slightly (0.5°-1°C cooler), and briefly, evidenced on the Alleghany Plateau (Shane and Anderson, 1993).

The post-YD increase in temperature and aridity was reinitiated at 10,500 yr BP and would be characteristic of much of the early to mid-Holocene in the eastern Midwest (Shane 1987). This warming also corresponded to a general increased aridity over the North American continental interior. This warming and increased aridity were caused by peak summer insolation, Laurentide Ice Sheet retreat, draining of Lake Agassiz, and a strengthened Bermuda subtropical high which together altered atmospheric circulation and regional hydrology in the early Holocene (Williams et al., 2010). The interval between 8000 and 4000 BP was characterized by maximum warmth in eastern North America. Drying appears to have been more extreme on the Till Plains, with the elevation of the Allegheny Plateau likely preventing such drying for the eastern half of Ohio (Shane 1987). Prairie conditions spread into western Ohio during this time after 8000 BP (Ogden, 1966; Shane, 1987; Williams et al. 2010). It is likely that increased insolation and the strengthened Bermuda sub-tropical high are the largest factors for the Mid-Holocene aridity in the Midwest (Diffenbaugh et al., 2006). Insolation is a driving factor in the amount of summer precipitation for the continental interior, and in the Mid-West the enhanced Bermuda high would yield stronger anticyclonic winds aloft bringing increases in descending stable, dry air for the region (Diffenbaugh et al., 2006). However, large heterogeneity exists at smaller spatial scales with local factors (topography, wind patterns, hydrology etc.) playing an important role in the timing and extremity of Mid-Holocene aridity (Williams et al., 2010).

Use of Chironomids

The majority of Quaternary paleoclimatic studies conducted in the Midwest have been pollen based (Shane, 1987; Shane, 1975; Shane and Anderson, 1993; Ogden, 1966). Chironomids, or non-biting midges, present an additional means to describe and quantify past climate and environmental change that has not yet been utilized in this region. Below the use of chironomids in paleoclimatic and paleolimnologic studies is reviewed.

Chironomidae (Insecta: Diptera) are a family of two-winged flies with an estimated 5000-15,000 species in existence worldwide (Brooks et al., 2007). The chironomid life cycle begins with an egg mass being deposited on the surface of a body of fresh water by a gravid female. The eggs hatch, and individuals move through the water column to the mud-water interface and proceed through four stages of larval growth. Each larval stage is called an instar, so the larvae that emerge from an egg would be called the first instar, and then the second instar and so on. As the larvae mature they shed their exoskeleton through a process known as ecdysis, growing progressively larger. The fourth larval instar transforms to a pupa which floats to the water's surface where it metamorphoses into adult form. It is the fourth instars' head capsule, which is heavily chitinized, that does not decompose in anoxic conditions and as a result can be extracted from lake sediment (Porinchu and Macdonald, 2003). The adult stage for midges is very short, typically lasting from a few days to a month, with the time sufficiently long to enable mating (Fig. 3). Midges are found in many environments, ranging from semi-terrestrial to freshwater aquatic ecosystems, and are associated with both lotic (lake) and lentic (stream) systems. Within lakes, the distribution of midge taxa is influenced by lake depth and bathymetry, lake temperature, and vegetation with distinct midge communities associated with bog and semi-terrestrial habitat and littoral and profundal zones (Brooks et al., 2007).

Chironomids are useful in paleolimnolgic studies for five main reasons (Porinchu and MacDonald 2003). First, midges are sensitive to important environmental variables including temperature, dissolved oxygen, and pH. Second, midges have short life spans, increasing the likelihood that the composition of midge communities reflects changes in the environment. Third, chironomids are mobile which allow adults to disperse in search of suitable habitats. Fourth, the larval head capsules, which are composed of chitin and resistant to decomposition, preserve morphological features that are diagnostic and sufficient to typically enable taxonomic identification at generic level. Fifth, midges are abundant in both species diversity and richness (i.e. there are many distinct species), which allows for detailed environmental studies and robust statistical analysis. Brooks et al. (2007) adds several more strengths of midges as general paleoecological indicators including: (1) many midges are stenotopic (they have narrow ecological optimums); (2) they live in virtually all aquatic habitats; and (3) midges can complement information gained from other proxies, allowing for detailed multi-proxy studies investigating several elements of environmental change.

It needs to be noted though that chironomids do have certain limitations in their use. As explained by Brooks et al. (2007), midge populations are influenced by many variables (pH, lake depth, etc.), which may confound the interpretation of records. For example, changes in midge community composition may result from increasing temperature but shifts in the relative abundance of particular taxa may be due to changes in lake level. Multiple proxies are analyzed in most paleolimnologic studies to facilitate the development of more robust paleoenvironmental reconstructions. Additionally, sub-fossil midges are rarely identified to the species level, possibly limiting the ability of midges to record subtle changes in lake conditions. Lastly, chironomid preparation and identification is a fairly time-consuming process, taking roughly 1-1.5 days per sample (Brooks et al. 2007). With these limitations in mind chironomids remain valuable proxies of past environmental conditions because they are very sensitive to fluctuations in air and water temperature. Temperature influences the rate of egg and larvae development as well as food availability (Porinchu and MacDonald, 2003) and as a result chironomid populations are generally most influenced by temperature (Brooks et al., 2007), allowing changes in temperature to be inferred by changes in the chironomid community.

The methodology for using chironomids as a proxy for environmental reconstruction is described by Porinchu and Macdonald (2003), and is based on the following assumptions: (1) that a relationship exists between chironomids and the targeted environmental variable; (2) chironomids leave identifiable remains; and (3) the sediment core from which the midges are extruded may be dated using radiometric techniques. The first step requires creating a training set or calibration set. Surface samples are gathered to create a record of the modern midge population from an array of lakes, usually about 50, along the desired environmental gradient (inter-lake training set). In lieu of a large lake set transects may be taken from a single lake at defined depth intervals to create an intra-lake calibration set. During surface sediment collection environmental variables are measured and recorded (temperature, pH, dissolved oxygen, sechi depth). In the lab chironomid samples are processed and identified (see Methods section for detailed procedure). Taxonomic identifications are based primarily on the size, shape and number of teeth found on the mentum and the size, shape and ornamentation of the ventromental plates (Fig. 4). Typically 50-100 midges head capsules are identified per sample. Multivariate statistical approaches such as ordination analyses are used to identify statistically significant relationships between the measured variables and midge distributions and then transfer functions are developed relating chironomid taxa abundance to a particular environmental variable. The calibration set can then be used to interpret the down core midge communities in light of what is known about the relationship between midge taxa and the modern environment. Generally, long sediment cores are recovered from the deepest point in a lake basin to ensure recovery of the longest possible sediment record. The sub-fossil midge community extracted from the deepwater sediment core is thought to well-represent the lake-wide chironomid population, as the remains of littoral taxa will be re-deposited in the center of the lake basin during lake mixing. After collection of the long core the sediment samples are prepared for midge analysis in a similar fashion to the surface samples. The richness (number of species present) data for individual taxa is converted to relative abundance data prior to its use in statistical analysis.

Methods

Field

Sediment cores and surface samples were retrieved from Smoot Lake near Utica in Licking County, OH. The bathymetry of Smoot Lake was determined using a GPS HumminBird Fishfinder and Dr. Depth software. The HumminBird Fishfinder, which was bow mounted on a Zodiac inflatable boat, recorded depth and position data along multiple transects. The depth and position data produced by the HumminBird was used as input to Dr. Depth, which in turn provided a 3D model of the lake basin (Fig. 5) as well as a contour map of lake bathymetry (Fig. 2).

Three sediment cores were collected from a floating platform using a modified Livingston piston corer in June 2010. Cores were collected from the deepest portion of the northern basin (~ 7m; deepwater core), from the middle of the slope of this basin (~4.5m; transition core), and from the saddle separating the two basins (~2m; saddle core) (Fig. 2). The cores measured 972 cm, 747 cm, and 420 cm respectively. Although multiple cores were collected, this project focuses on the core recovered from the central basin. Upon extrusion the cores were described, with obvious contamination identified and discarded. The cores were placed in 2" PVC tubes for transport to The Ohio State University for further laboratory analyses. In addition to collecting the Holocene sediment cores a suite of surface samples were also recovered from Smoot Lake. The surface samples (0-1 cm) were collected at 0.50m depth intervals along three transects radiating outward from the coring platform using a DeGrand corer. During surface sediment recovery limnological variables including surface and bottom water temperature and pH were recorded using an YSI 556 multi-parameter meter. Additional Holocene sediment cores and surface samples were collected at Brown's Lake in Shreve, Wayne County, OH using similar methods as a part of the larger study (Fig. 1).

Laboratory

The sediment cores were split in the lab and described for texture, stratigraphy, and color. Images of the discrete core sections were taking using a rock core scanner at Byrd Polar Research Center at The Ohio State University. A composite image of each of the sediment cores was created in Photoshop. These images were used to identify stratigraphic relationships amongst the three cores. Stratigraphic descriptions together with a detailed analysis of the composite core imagery enabled identification of additional contaminated sediment. The contaminated sediment was removed from the affected core sections resulting in the length of the deep-water core being reduced by 4 cm relative to the length of the core as measured in the field. Stratigraphic analysis identified that a clay-rich layer characterized the uppermost portion of each core. This clay deposit, which varies in thickness (181cm-121cm), is associated with land use clearance and agriculture runoff and was likely deposited during the past 200 years and as a result was not used in subsequent analyses. The deepwater, transition, and saddle cores were sectioned at 0.5 cm intervals and stored in Whirl-paks at 4°C until needed for further analysis.

During sectioning, organic material was isolated for AMS dating. Chronologic control for the deep-water core is provided by 5 AMS 14C dates. The radiocarbon analyses were conducted by Beta Analytic (Miami, Florida). The material used for these dates include aquatic moss, wood, and bulk sediment (Fig. 6). The 14C dates were converted to calibrated ages (cal yr BP) using CALIB v. 6.0.1 (Reimer et al., 2004). The midpoint of the 2σ cal yr age range with the highest probability of occurrence was utilized to develop the age–depth model (Telford et al., 2004). The age–depth model is based on a cubic regression (Fig. 7).

Percent loss on ignition (LOI), which provides an estimate of the total amount of organic carbon in a sample, was performed according to standard procedures (Heiri et al., 2001) at 4 cm intervals with 1 mL of sediment used in the analysis. Each sample was weighed wet, dried in an oven for 24 hours at 100°C, and then weighed dry. The dry samples were placed in a furnace at 550°C for 4 hours, causing organic carbon to combust. The ash weight of each sample was then recorded. LOI is then calculated by ((dry weight-ash weight) / dry weight) * 100. LOI is a useful proxy to describe lake productivity, with LOI values positively correlated with lake productivity.

Carbon to nitrogen (C:N) ratios offer a measure of the amount of terrestrial versus aquatic organic matter in a sample. Algae (autochthonous source) typically have a C:N ratio between 4 and 10, whereas terrestrial organic material (allochthonous source) typically have C:N ratios of greater than 20 (Meyers, 2003). C:N, which reflects environmental conditions within the catchment and lake, has been used to identify the timing of deforestation as well as changes in lake productivity (Kaushal and Binford, 1999). A total of 78 1 mL sub-samples were dried, ground up using a mortar and pestle and sent to the University of Hawaii where they were analyzed by Dr. David Beilman.

Sub-fossil chironomid analysis provides a useful proxy to measure environmental change. Chironomid analysis was performed according to standard procedures (Walker, 2001). Samples of at least 0.5 mL of sediment were taken at 25 cm intervals along the entire length of the deep-water core from Smoot Lake. Sediment samples were washed in a 10% KOH solution at about 30°C for 25 minutes to break up colloidal material, passed through a 95 µm sieve to isolate chironomid head capsules, and then backwashed into a beaker. Chironomid head capsules were manually picked from a Borogrov plankton counting tray using a Zeiss Stemi 2000-C Stereo microscope at 50X using tweezers and placed on a cover slip with distilled water. Once the distilled water evaporated the cover slip was permanently mounted using Entellan®. Head capsules were identified using Brooks et al. (2007) with a Zeiss Axioscope 2 Plus light microscope at 400X magnification. A minimum of 46 identifiable head capsules were identified in the 34 samples analyzed in this study. The raw midge data were entered into a spreadsheet, converted into relative abundances and then imported into C2 to create a relative abundance diagram (Fig 8). The diagram was zoned using BSTICK. Shannon's H (Fig. 9) is a diversity index measuring species evenness while incorporating diversity, with higher values indicating more evenness and diversity (i.e. the relative abundances of different taxa are closer together) (Meerman, 2004) and was calculated using PAST (Hammer et al., 2001).

Results

The stratigraphy of the 968cm basin core (LC2) from Smoot Lake is composed of distinct layers, with the deepest being one of banded sediment between 968 and 609 cm (Fig. 10). The next layer is composed of consistent dark sediment from 609 to 181 cm followed by a molted clay layer form 181cm to the surface. A sand lens is present at 528.5 cm which may correspond to another sand lens located in the transitional core (LC3). Occasionally blue flecks are found at numerous places throughout the core which are believed to be vivianite; an iron phosphate mineral (McGowan and Prangnell, 2006).

The cubic age-depth model, which yielded the curve and equation seen in Fig. 7, was used to calibrate the age of the core. In addition to the radiometric dates a sixth date was applied to the model correlating the beginning of the molted clay layer (181cm) to 1850 AD. Construction of a nearby railroad began in the 1840's which, with the beginning of established farms in the region (Hill, 1881), is likely responsible for the rapid accumulation of clay. The core has a basal depth of approximately 10,300 BP. Based upon this model and identified sediment zones, sedimentation rates appear to be roughly 0.08 cm/year of sediment for the banded sediment layer and approximately 0.09 cm/yr for the dark sediment layer. Transition zones appear to be at 5228 BP and 1850 AD. The upper molted clay layer contains a sedimentation rate of approximately 1.12 cm/year. Contributing this layer to be the consequence of land clearance with modern farming practices as well as nearby rail construction, this sediment is not used in subsequent analysis.

LOI shows organic content beginning at 60% at the base of the core. It decreases rather quickly to be between about 30% and 50% around 9,500 BP where it remains so until about 6,000 BP when it begins to rise again. LOI rises to between 60% and 90% at 5,500 BP and remains relatively stable except for a short dip to below 60% around 3,500 BP before rising again to 80% at about 3000 BP. Organic content then very quickly plummets to about 10% for very recent time, which is associated with the beginning transition to molted clay and modern processes (Fig. 11).

The trends in the C:N are similar to those apparent in the LOI profile although the variability in the C:N data is reduced relative to LOI. The C:N ratio is relatively high at the base of the sediment record with a core maximum value of 13 occurring at ~ 10.5k yr BP. The C:N decreases rapidly during the early Holocene reaching a core minimum at 8100 yr BP. The interval between 8100 and 4500 yr BP is characterized by increasing but fluctuating C:N values. A notable increase in C:N occurs at ~ 3800 yr BP when the measured value nearly reaches 13. The post-3800 yr BP interval is characterized by decreasing C:N, with the C:N of sediment deposited in the last 200 measured to be 8.5.

The Smoot Lake chironomid stratigraphy was partitioned into three statistically significant zones (SML-1 to SML-3) determined using optimal sum of squares partitioning as implemented by ZONE (Juggins, 1992) with the statistical significance of the zones assessed using BSTICK (J.M. Line and HJ.B Birks, unpublished program) (Fig. 8).

SML-1 (10,350 – 9300 cal yr BP; 965-875 cm)

This zone is dominated by five taxa: *Labrundinia* (~10%), *Dicrotendipes nervosus* type (20%), *Gylptotendipes pallens* type (~8%), *Polypedilum nubeculosum* type (~15%), and *Procladius* (10%). The midge community is relatively depauperate, with only 30 taxa present. The taxa that are present are representative of bog (*Labrundinia*), littoral (*Dicrotendipes nervosus* type, *Gylptotendipes pallens* type) and profundal environments (*Procladius*). The presence of relatively high abundances of bog, littoral and profundal taxa, as well as a steadily rising Shannon's H (Fig. 9), suggests that the early Holocene at Smoot Lake was characterized by dynamic and fluctuating limnological conditions.

SML-2 (9300 -5750 cal yr BP; 890-575 cm)

This zone is dominated by four taxa: *Labrundinia* (~30%), *Corynoneura spp.* (10%), *Polypedilum nubeculosum* type (~15%), *Procladius* (10%). The richness of the midge community increases in this zone, reaching a value of 40. However, a consistent decrease in Shannon's H (Fig. X) indicates a decrease in species evenness. Although the bog, littoral and profundal midge communities are well-represented in SML-2, a notable decrease in the relative contribution of littoral taxa to the overall midge community composition is observed. For example, littoral taxa such as *Dicrotendipes nervosus* type, *Dicrotendipes notatus* type, *Endochironomus, Gylptotendipes pallens* type and *Gylptotendipes severini* type, decrease in relative abundance through this zone. The appearance of *Micropsectra* and a notable increase in *Chironomus*, two taxa typically associated with profundal environments, also characterizes this zone. The increase in the abundance of profundal taxa relative to overall midge community composition suggests that Smoot Lake during this interval was characterized by decreases in the amount of habitat suitable for littoral taxa.

SML-3 (5750 – 100 cal yr BP; 575 – 180 cm)

Although the species richness in SML-3 is similar to SML-2 the midge community is characterized by greater species evenness as indicated by a larger Shannon's H (Fig. 9). In this zone the community is not dominated by 3-4 midge taxa as in SML-2. The dominant midge taxa in SML-3 are: *Labrundinia* (~15%), *Dicrotendipes nervosus* type (20%), *Polypedilum nubeculosum* type (~8%), *Tanytarsus pallicornis* (10%), *Paratanytarsus* (10%), *Micropsectra* (~8%), *Tanytarsus mendax* (10%), *Tanytarsus* (undifferentiated) (10%). The relative contribution of bog taxa to the overall midge community composition and diversity increases in this zone. Increases in littoral taxa also characterize SML-3 with an increase of *Dicrotendipes nervosus* type reaching early Holocene values at the onset of the interval encompassed by SML-3. Increase in the diversity and abundance of bog taxa as well as the decrease in profundal taxa abundances during SML-3 indicates the increasing importance of the surrounding bog environment on Smoot Lake's midge community composition during the late Holocene.

Discussion

Lake bathymetry has been demonstrated to have a large impact on the overall composition of the midge community in aquatic ecosystems (Luoto et al. 2012; Engels and Cwynar 2011; Kurek and Cwynar 2009). The bathymetric structure of a lake will affect a number of variables including: available amount of littoral habitat, depth of the euphotic zone and hypolimnetic volume to name a few. Although many midge genera can live in a variety of aquatic habitats, i.e. throughout the lake basin, most midge taxa are associated with specific zones within a lake. These zones, which are based on the structure of the lake basin, can be broken into three general categories: (1) bog/semi-terrestrial (very near shore and/or in very shallow water); (2) littoral (near shore up to approximately 5 meter deep water where light penetration permits aquatic plants to survive; and (3) profundal (below 5 meter with little to no vegetation) (Brooks et al., 2007). For example, *Procladius* (Fig. 4K) is typically associated with the profundal, whereas *Polypedilum nubeculosum* (Fig. 4J) is most commonly found in the littoral zone of temperate lakes. The depth of a lake, which influences many factors including thermal stratification and lake water stability, wind mixing, oxygen concentration, light, and food availability, also affects chironomid distribution (Porinchu and MacDonald, 2003). The effects of bathymetry (lake basin structure) and lake depth are largely responsible for the observed intra-lake variation in midge community composition.

Previous studies have shown that sub-fossil midge remains can prove a valuable proxy of lake depth (Luoto, 2012; Engels and Cwynar, 2011; Kurek and Cwynar, 2009)). In this study, changes in the relative abundance of littoral taxa are interpreted as salient indicators of lake level change. Changes in lake level will affect the relative availability of bog, littoral, and profundal habitat, which in turn will be reflected in the abundance of specific midge, i.e. bog, littoral and profundal taxa. Fluctuations in the relative abundance of bog, littoral and profundal midge taxa can therefore be used to track changing lake levels and help in the production of regional reconstructions of changes in effective moisture.

Smoot Lake, which is composed of two basins separated by a shallow sill, has a relatively complex bathymetric structure and changes in lake level will dramatically alter the amount of available littoral and profundal habitat. Although possibly counter intuitive, in Smoot Lake a decrease in the percent of littoral taxa has been inferred to indicate decreasing lake levels. The reason for this is illustrated in Figs. 2 and 5. Smoot Lake is characterized by a shallow shelf which surrounds the deep central basin. If the water level were to decrease, the surface area of available littoral habitat would decrease while the habitat for profundal species in the deep basin would be minimally affected, if at all.

As can be seen in Fig. 8, zone SML-1 (10,350-9,300 cal yr BP) is characterized by a mixed chironomid assemblage with high relative abundances of taxa associated with all three lake habitats. This likely reflects regional climate and environmental instability during the early Holocene with lake levels at Smoot Lake experiencing notable fluctuations. During the interval captured by SML-2 (9,300-5,750 cal yr BP) the relative abundance of littoral taxa, which begins to decrease at the base of the zone, reaches a core minimum at 8500 cal yr BP and stays relatively low (~30-50%) until rising at ~ 7000 cal yr BP (Fig. 10). It needs to be noted that head capsule concentration is lowest during SML-2 with the relative contribution of profundal chironomids to the overall midge community increasing during this zone (Fig. 8). This decrease in littoral taxa, which likely reflects a reduction in littoral habitat availability, may be due to lower lake levels isolating the deep central basin and is indicative of a millennial long period of decreased effective moisture. The data from Smoot Lake suggests that mid-Holocene aridity in Ohio may have begun earlier than previously thought (Shane 1987). The rising abundance of littoral taxa as well as the large increase in head capsule concentration that occurs after 7,000 yr BP indicates that lake levels began to rise during the mid-Holocene. Stable conditions appear to begin around 5750 cal yr BP with the beginning of zone SML-3 (Fig.11). A noticeable dip in littoral taxa appears again at about 3,500 cal yr BP (Fig. 11) which is suggestive of lower lake levels at this time and another prolonged, albeit shorter, intense regional drought.

Organic carbon content as estimated by LOI follows the same general trends as percent littoral taxa (Fig. 11) giving additional support to the timing of lower lake levels and drought. It would be expected that lower lake levels would reflect lower organic carbon content due to overall less surface area for autochthonous productivity. Furthermore, LOI would also be expected to decrease in times of low lake level due to the interconnectedness of Smoot Lake. Being a double basin lake, organic material is exchanged between both basins at present. It is probable that lake levels fell enough during the millennial scale drought at approximately 8,500 cal yr BP to create two single basin lakes effectively limiting exchange of sediment between the basins, which is reflected in the consistently low LOI values around this time. The dip in LOI at 3,500 yrs BP is not as severe or as long as the early Holocene sequence suggesting lake levels did dip here as well though to a lesser extent. The values may reflect some interconnectedness between the lake basins, suggesting a slight decrease when compared with the 8,500 yrs BP event.

The C:N ratios reflect the pattern of percent littoral taxa and LOI suggesting the timing of low effective moisture around 8,500 yrs BP. The C:N ratios function similarly to LOI values regarding basin connectivity. Higher values are associated with more connectivity, as it is easier for terrestrial matter to be washed into the lake. The lack of lower C:N values at 3,500 yrs BP suggest that this event is possibly not significant to register a change. The relatively high value (about 13) is only recorded in a single sample so is likely not indicative of any event. It is interesting to note that C:N ratios fall and do not rise at the end of the core in recent times as would be expected from deforestation (Kaushal and Binford, 1999). Possible reasons for this may include an influx of materials associated with rail construction which may alter the record.

A general agreement exists that periods of the Holocene were warmer and drier for the interior of North America though a consensus does not exist for exact temporal or spatial scales of these events (Shane, 1975; Shane, 1987; Shane and Anderson, 1993, Williams et al., 2010). In the early to mid-Holocene an extensive aridity has been noted for much of North America between 8000 and 4000 yrs BP (Shane, 1987). Reports of millennial scale localized warming and drying events however extend back to 10,000 BP in Ohio (Shane, 1975). Although local responses often differ from regional trends (Williams et al., 2010) our study suggests that the warming and drying trend of the mid-Holocene began in the early Holocene for central Ohio, reaching its full extent by 8,500 yrs BP. It is likely that the extensive aridity was amplified by the collapse of the Laurentide Ice Sheet (8,400 yrs BP) which contributed greatly to ground water recharge (Williams et al., 2010).

The Mid-West as a region generally experienced drying by 7,500 (Williams et. al.) with a period of maximum warmth extending to 4,000 yrs BP (Shane, 1987). Although our study does not capture evidence of an event at the postulated 6,000 yrs BP in the Holocene Thermal Maximum, our study does indicate drying and lowering of lake levels for a substantial length of time centered around 3,500 yrs BP. It may be that due to local factors the regional aridity was not noticed in central Ohio until the late Holocene. Although the aridity appears less severe than the early Holocene less factors are contributing to this event (there is no disappearing ice-sheet which provided ground water recharge for example) so the decrease in effective moisture may be due to less precipitation. This suggests that if climatic conditions were to return to those of the mid-late Holocene Ohio would indeed experience decreases in effective moisture and suffer, among other consequences, drought and lower lake levels which would have severe societal and economic ramifications.

Summary and Future Research

This study has found evidence of a decrease in effective moisture by inference of lake level change from isotopic and biological proxies for the early and mid-late Holocene. Changes in relative abundance of insects grouped by their habit along with LOI and C:N ratios have proven to be valuable and reliable indicators of lake level fluctuations. However, a network rather than solitary sites provides a better understanding of environmental change for a region

(Glover et al., 2011). More analysis needs to be done on multiple study sites to give a robust interpretation of aridity throughout the Holocene in Ohio. Similar analysis needs to be performed on the sediment cores from Browns Lake as well as additional cores collected from surrounding areas. Although suitable sites are rare in Ohio due to extensive development, a particularly useful site may be the shallow basin from Smoot Lake. This record would provide a useful analogue to the deep basin. Further useful work would be to create transfer functions relating midges to water depth in order to quantify lake level change.

Project revisit

Throughout the two years I have worked on this project I have gained extraordinary experiences through laboratory and field work. I have gained invaluable experience learning the methodology and functioning of scientific research early in my career which will prove extremely useful in the future. I have had a hand in every facet of this project from the collection of sediment cores at Smoot Lake in June 2010 to conducting the analysis of LOI and learning chironomid identification. Were I to re-do aspects of this project, I would focus my efforts on the two deep cores from Smoot Lake and Browns Lake and use a higher resolution of chironomid samples to give a more detailed analysis. The deep core at Browns Lake would yield a very valuable complementary suite of information, and I am curious as to how the records correlate.

Figures

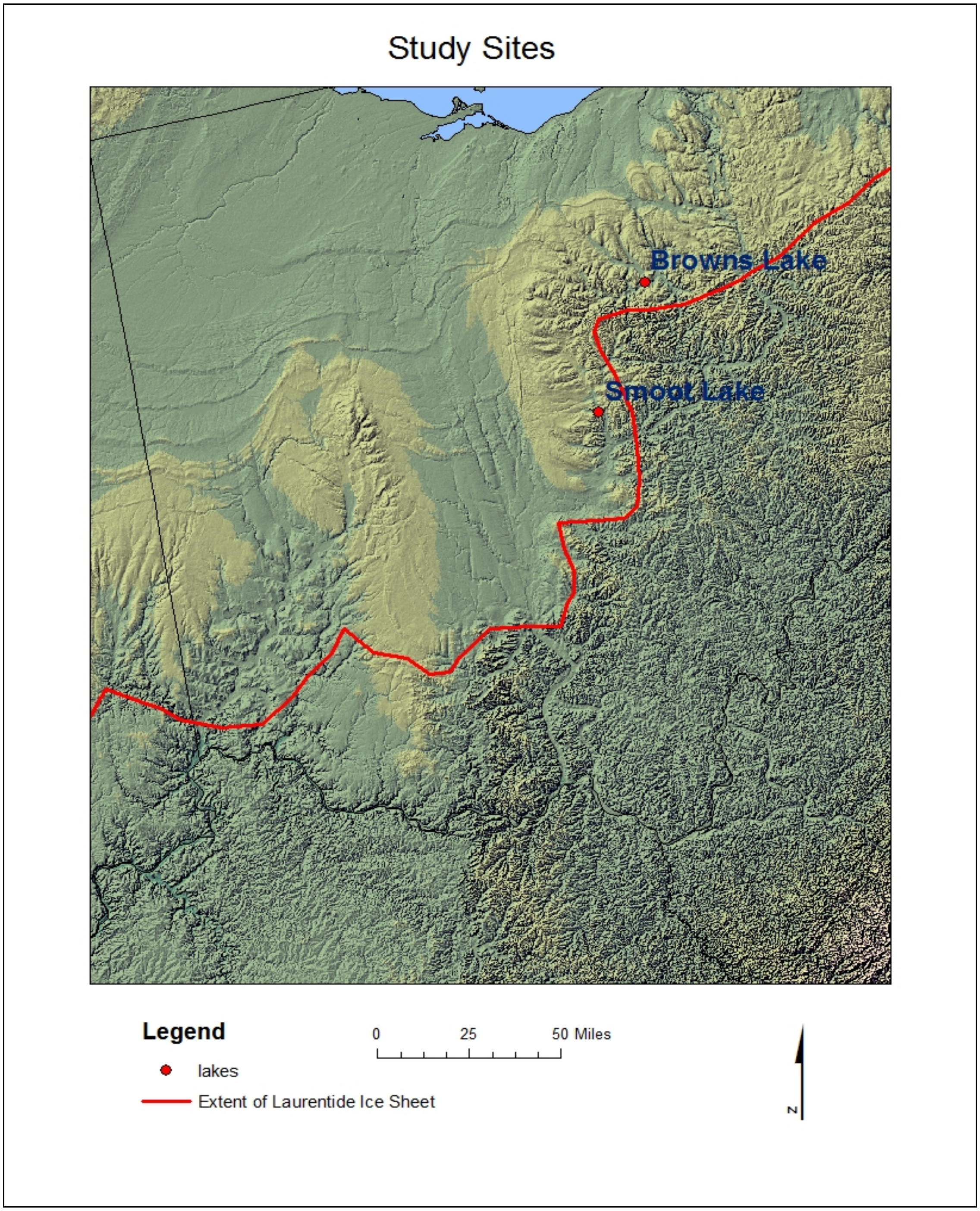

Fig. 1: Location of Browns Lake and Smoot Lake in Central Ohio and extent of the Laurentide Ice Sheet during the Last Glacial Maximum. DEM provided by USGS seamless server.

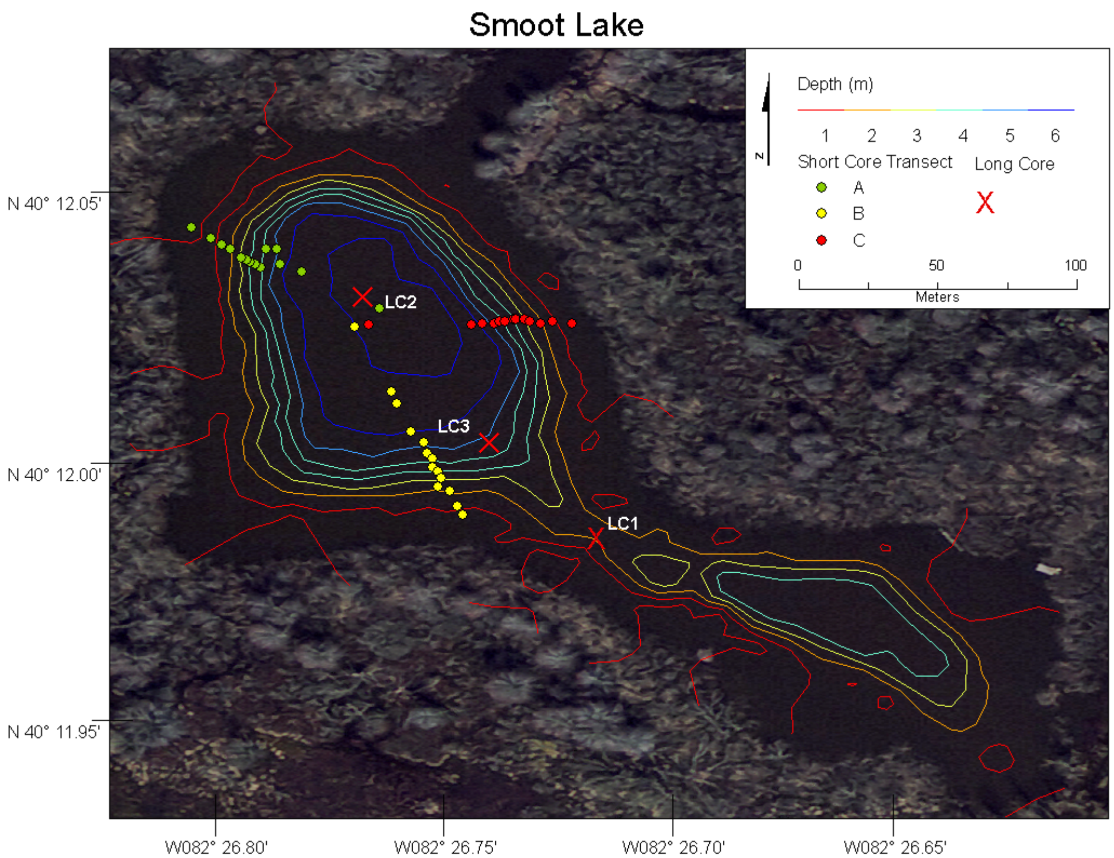

Fig. 2: Smooth Lake bathymetry and the locations where surface and long sediment cores were recovered. Surface samples (short cores) were taken along transects from the shore to the center of the basin at depth intervals of ~ 0.50 m. Three long (Holocene) sediment cores were also recovered from Smoot Lake (coring location = X). Background image provided from the USGS Seamless Server.

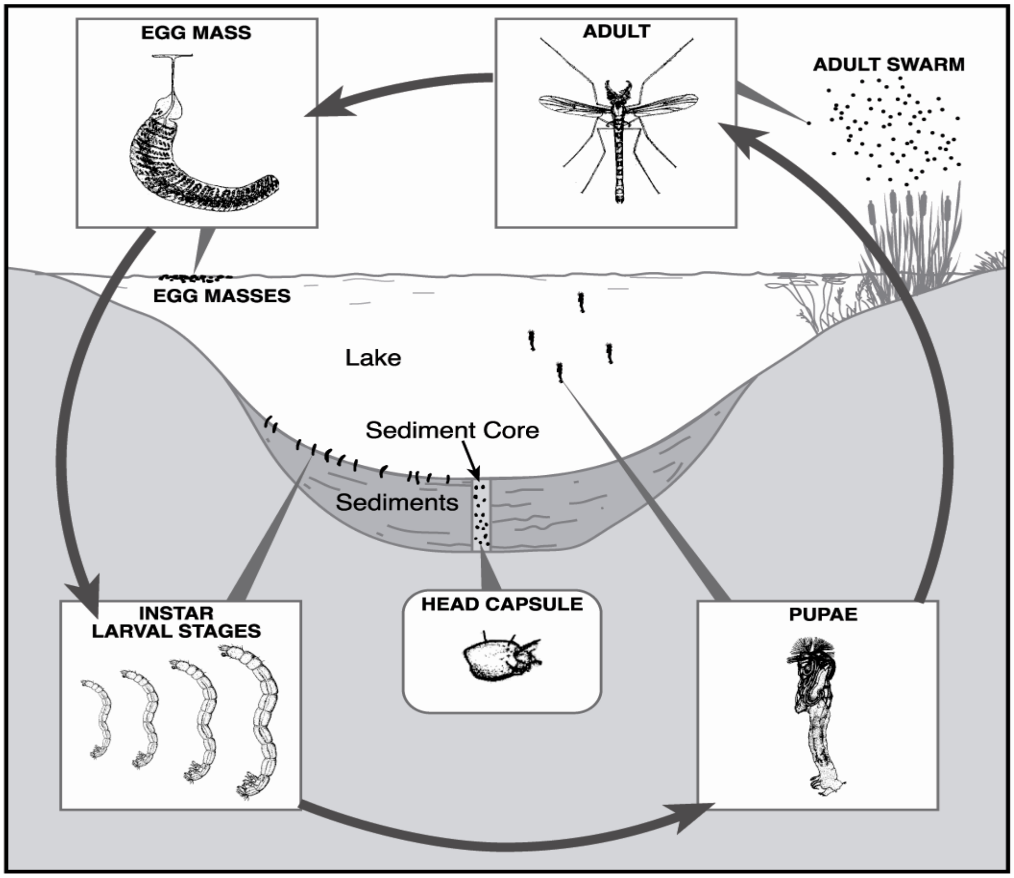

Fig. 3: A schematic depicting the stages of the chironomid lifecycle. Taken from Porinchu and MacDonald (2003).

Fig 4A: Chironomus

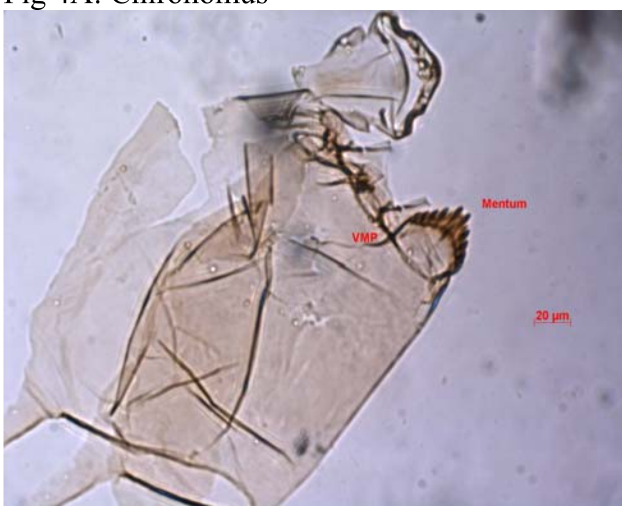

Fig 4B: Corynoneura

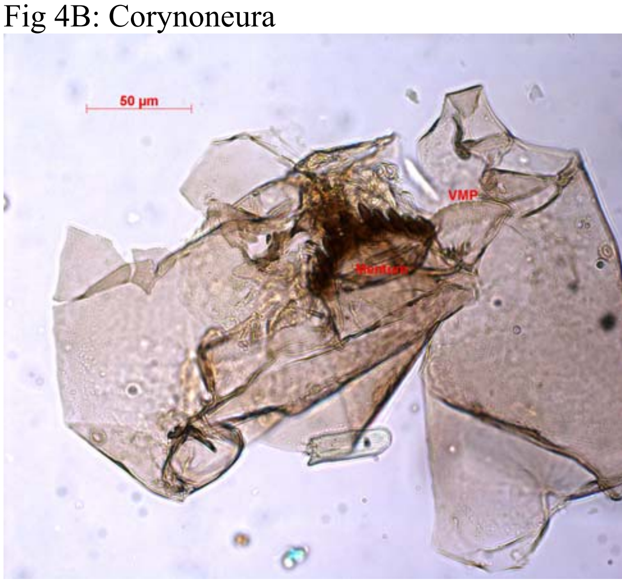

Fig 4C: Dicrotendipes nervosus

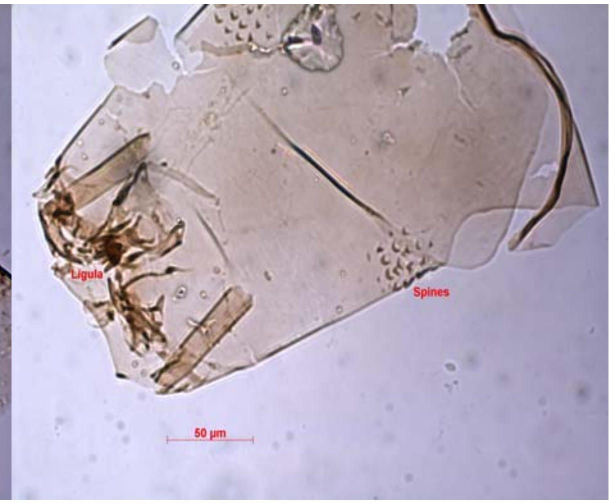

Fig 4D: Labrudinia

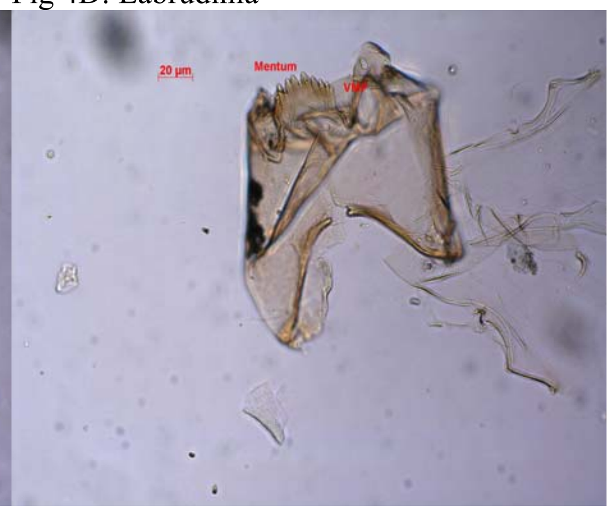

Fig 4E: Lauterborniella

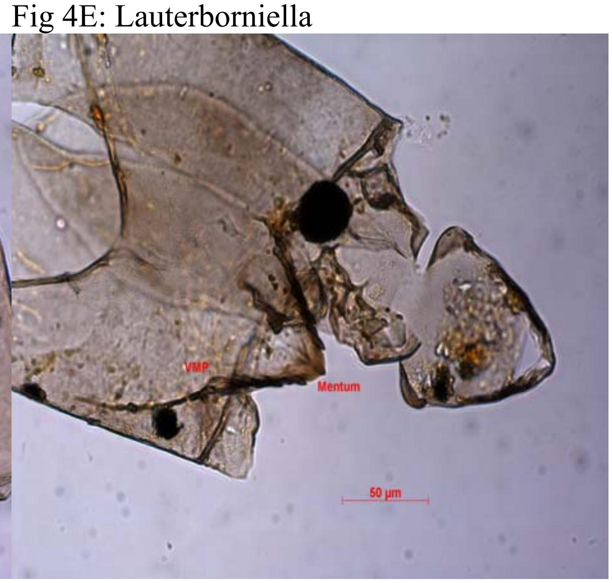

Fig 4F: Parakiefferiella bathophila

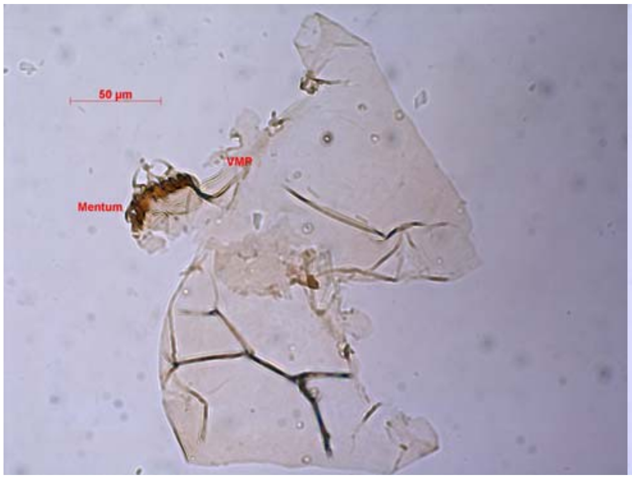

Fig 4G: Paratanytarsus

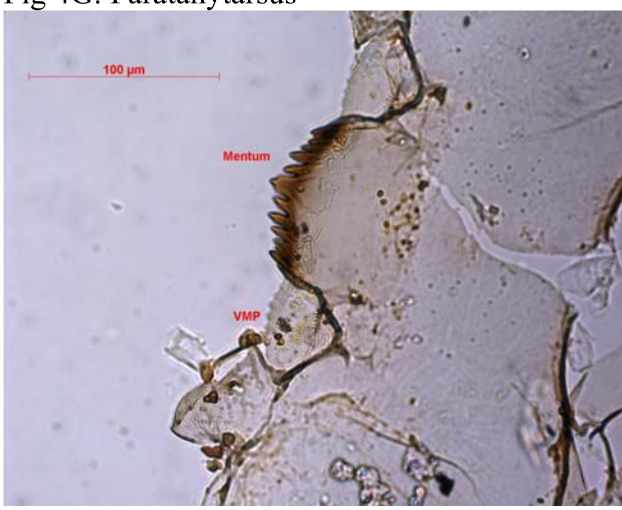

Fig: 4H: Parachironomus

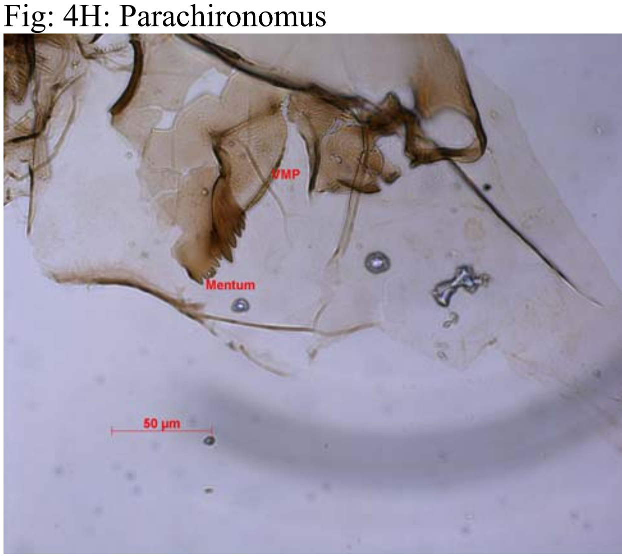

Fig 4I: Paratendipes

Fig 4J: Polypedilum nubeculosum

Fig 4K: Procladius

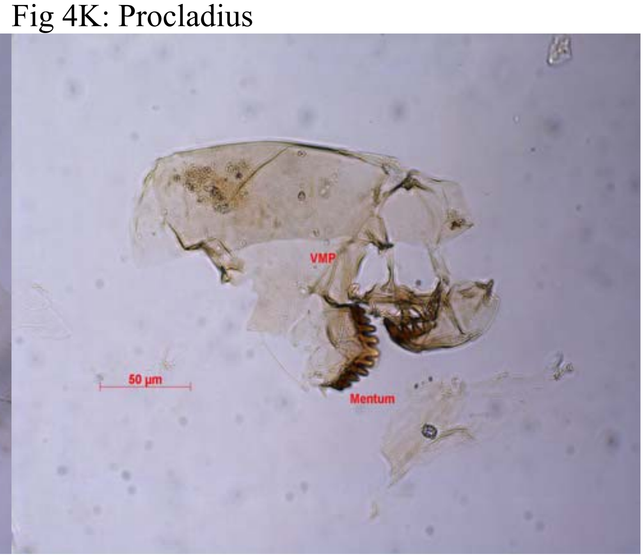

Fig 4L: Tanytarsus pallidicornis

Fig. 4: Color plates of common midge head capsules encountered in the Smoot Lake sediment core. The mentum and ventromental plate (VMP), the key diagnostic features used to identify the head-capsules, are labeled.

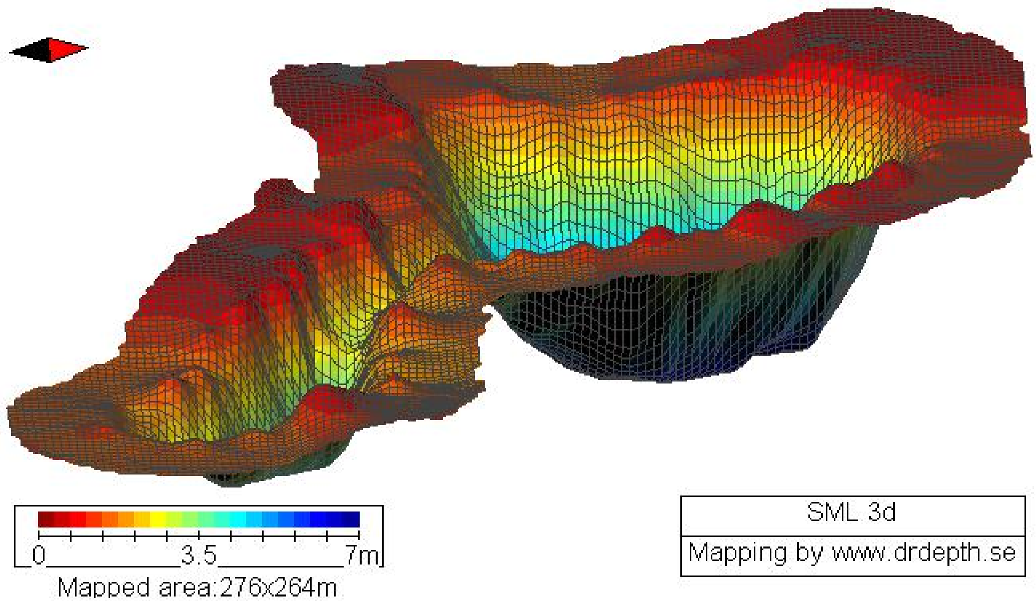

Fig. 5: A 3D bathymetric map for Smoot Lake developed using the output generated by a HumminBird fish finder, and processed by Dr. Depth.

Lab Code	Depth in Core (cm)	Material	^{14}C yr BP	±	2 σ range (Cal yr BP)	Midpoint age (Cal yr BP)
292056	625	Woody Plant Material	5840	40	6740-6550	6645
284051	956.5	Plant Fragments	9170	40	10480-10240	10360
284050	447	Woody Plant Material	3660	40	4080-3875	3980
281639	704	Plant Fragments	6270	40	7270-7160	7215
281638	305	Woody Plant Material	2100	40	2290-1980	2065
281637	388.5	Wood	240	40	420-270	295

Fig. 6: AMS 14C data for the Smoot Lake core. Lab code refers to the Beta Analytic sample number.

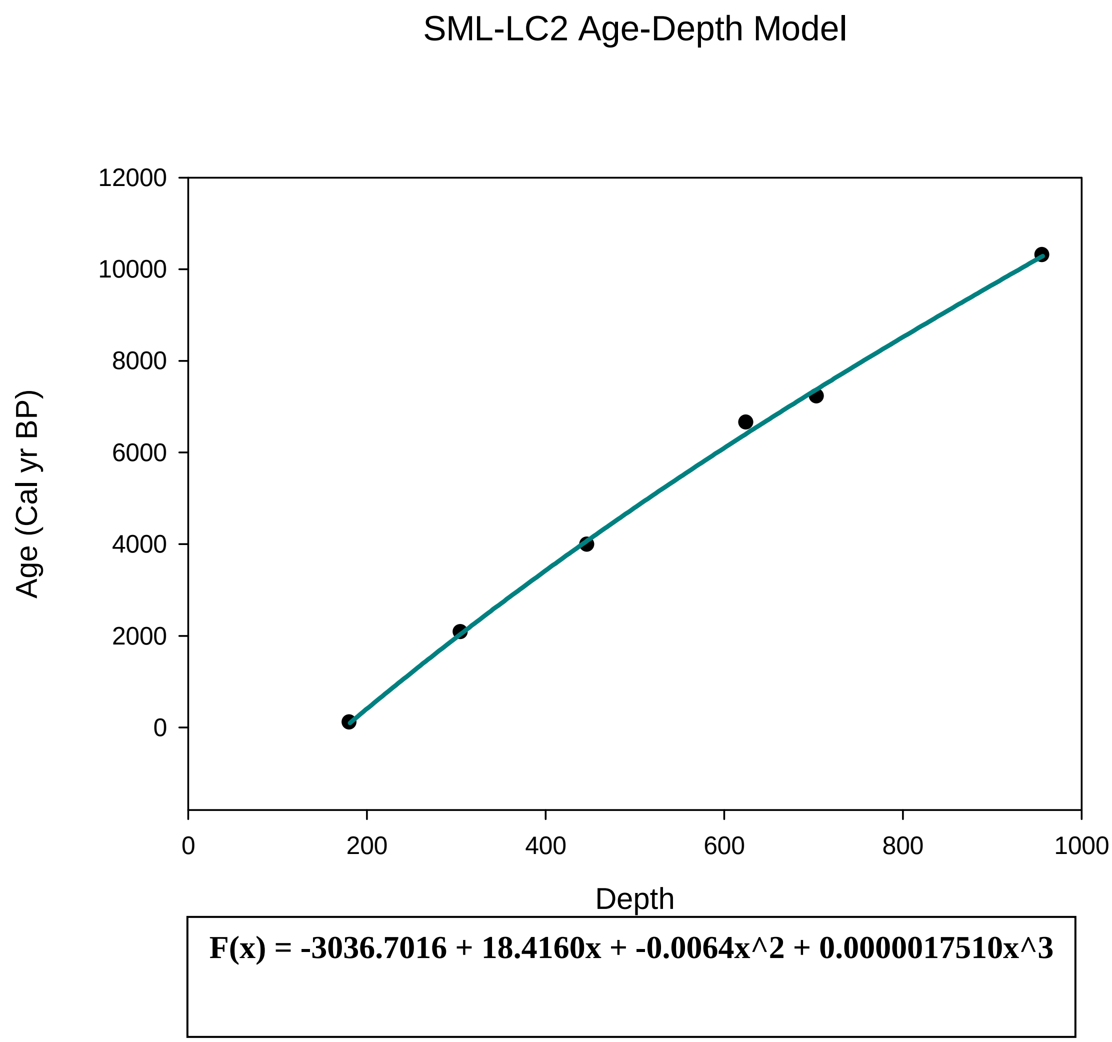

Fig. 7: Age-depth model for the sediment core from Smoot Lake. Cubic age-depth model fit through five calibrated 14C dates and depth 181cm (estimated beginning year of rapid sedimentation from agriculture and rail construction (Hill, 1881)).

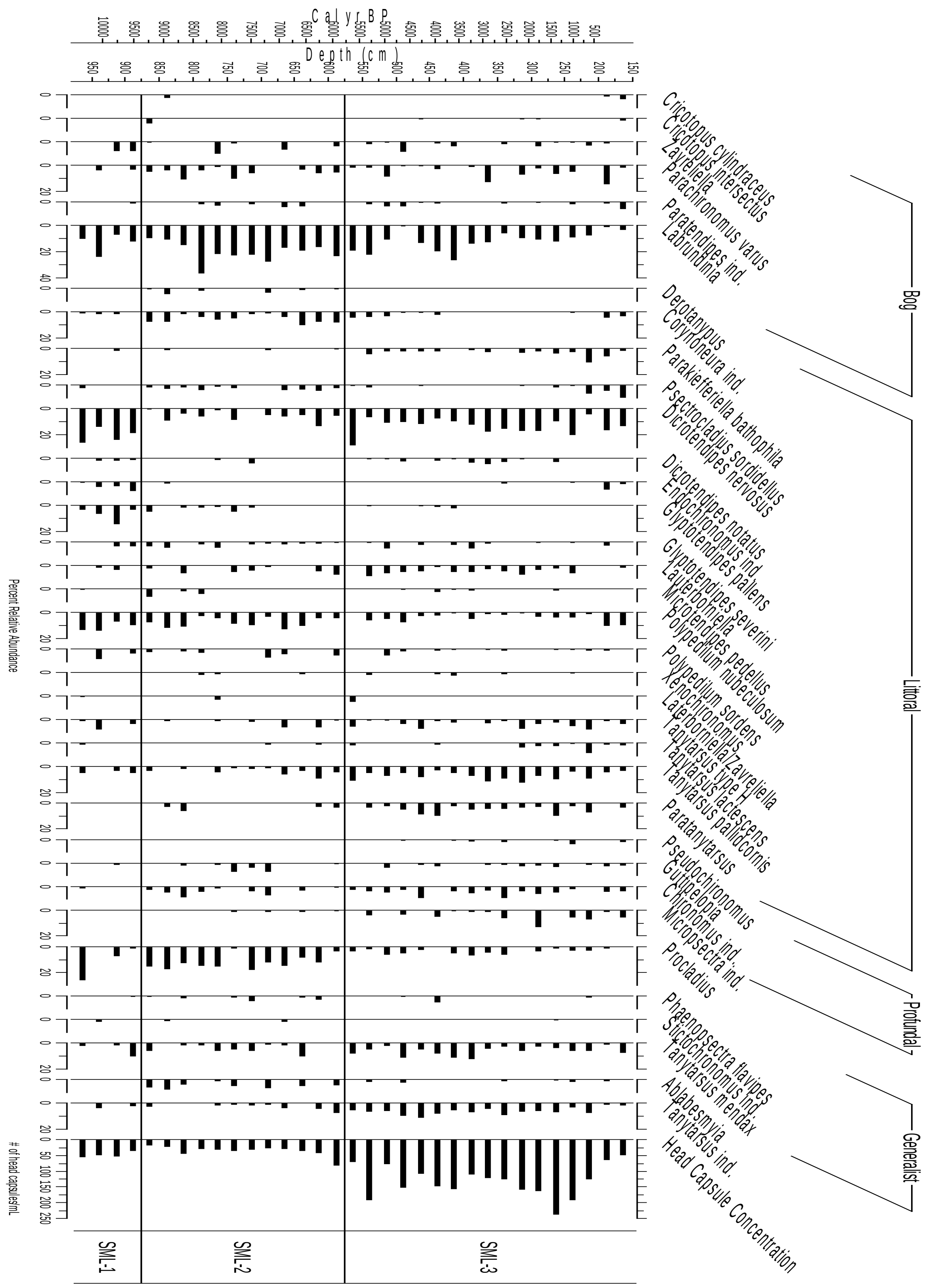

Fig. 8: Chironomid relative abundance diagram and head capsule concentration (head capsules per mL of sediment) for Smoot Lake. The midge taxa have been grouped according to known aquatic habitat preferences based on Brook et al. (2007).

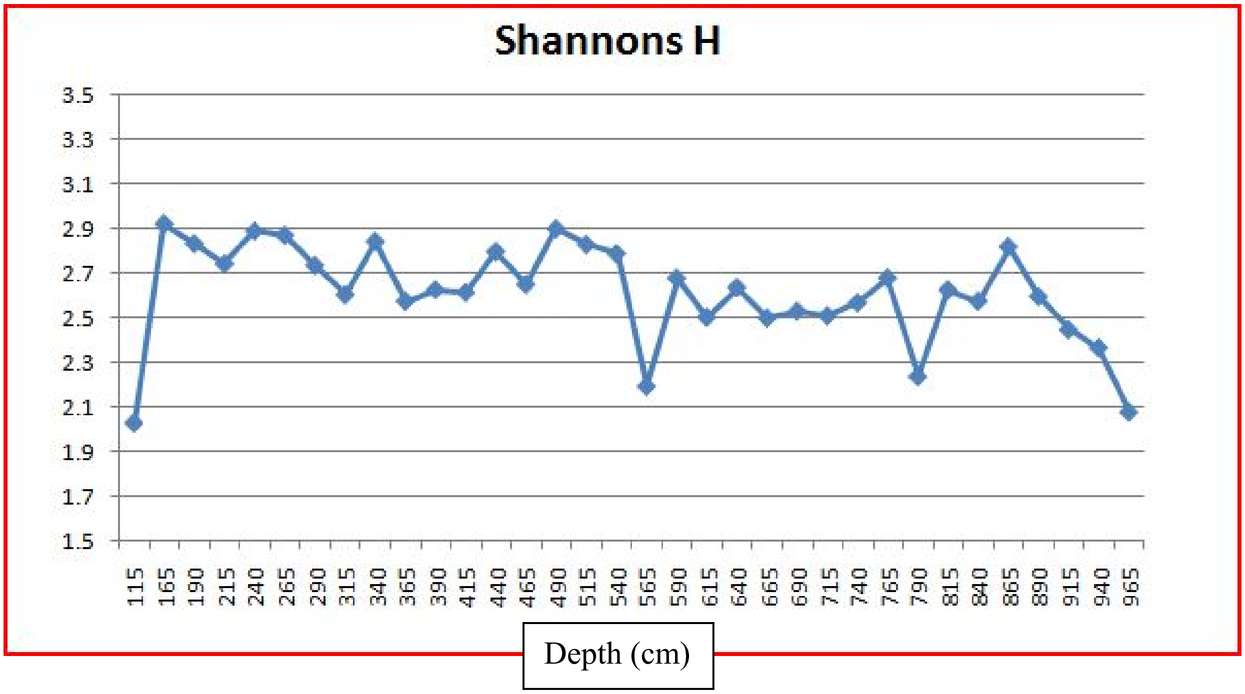

Fig. 9. Shannon's H diversity index plotted against each chironomid sample depth. Higher values indicate more species diversity (more richness) and evenness.

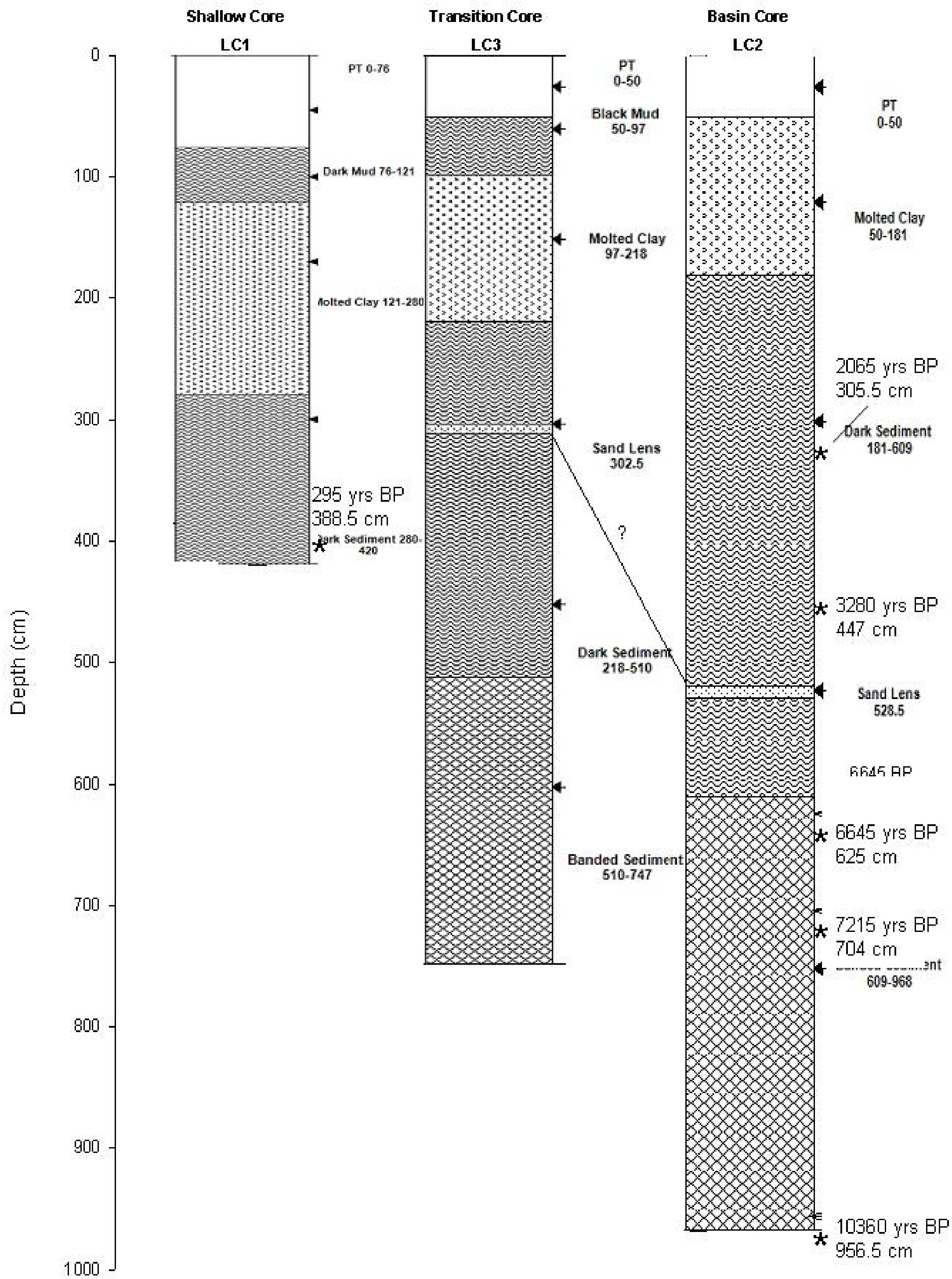

Fig. 10: Stratigraphy of the three Holocene cores (LC1, LC2, LC3) recovered from Smoot Lake. Asterisks (*) denote locations of C14 dates with corresponding ages and depths.

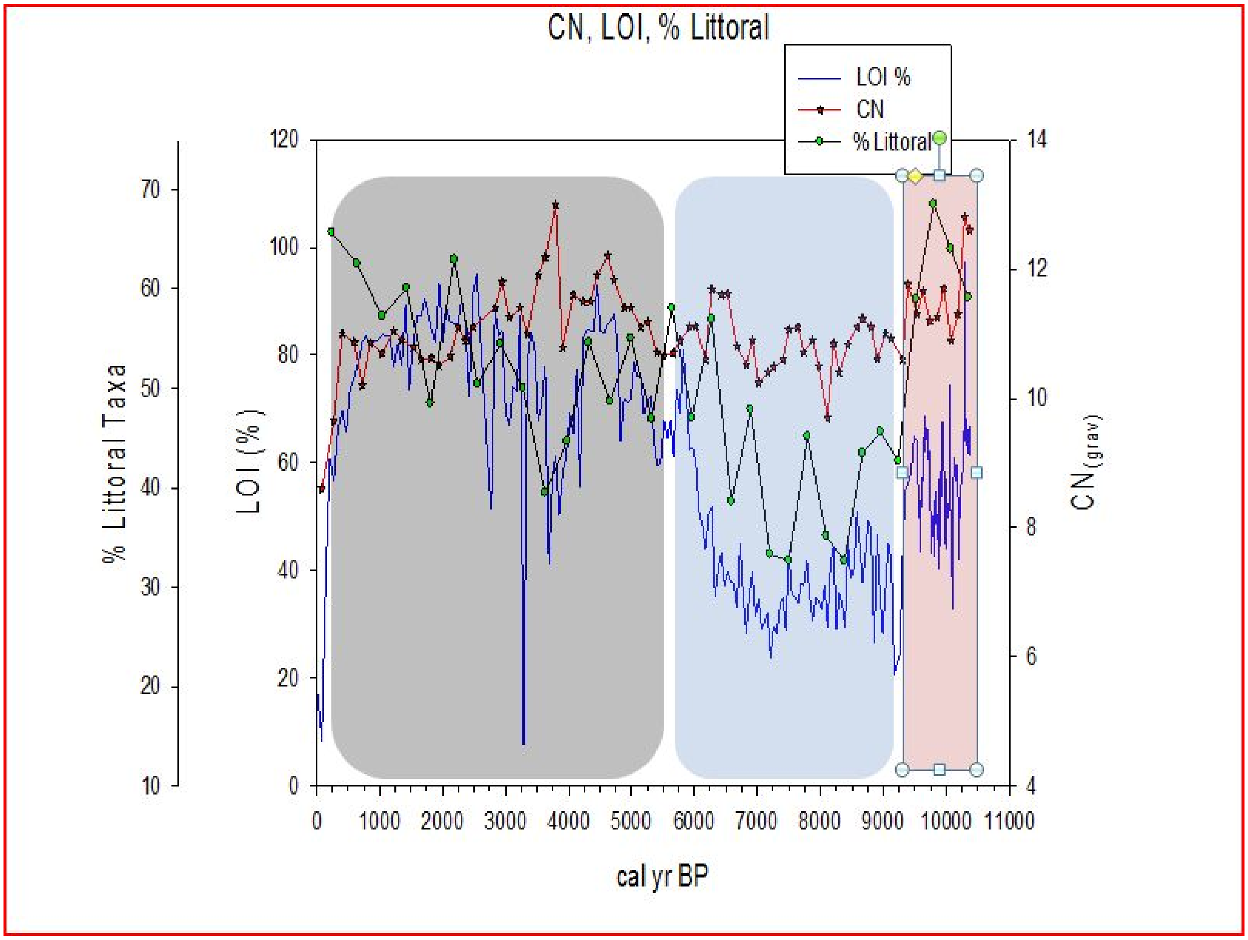

Fig. 11: Summary diagram depicting LOI, C:N and percent littoral chironomid taxa for SML-10-LC2. The red shading indicates Zone SML-1, blue Zone SML-2, and purple Zone SML-3.

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